workloads can be balanced among the steps, i.e., $[\vartheta_{1L}, \vartheta_{1U}] \cap [\vartheta_{2L}, \vartheta_{2U}] \cap \ldots \cap [\vartheta_{nL}, \vartheta_{nU}] \neq \emptyset$. By Algorithm 4.1, one can find an optimal feasible schedule for the close-down process. Thus, the robot waiting time is set as follows: 1) During the process from M_{c1} to M_{c2}, $\omega_0=\omega_1=\omega_2=\omega_3=\omega_4=0$ s and $\omega_5=52$ s: 2). During the process from M_{c2} to M_{c3}, $\omega_2=\omega_3=\omega_4=0$ s and $\omega_5=71$ s; 3) $\omega_3=\omega_4=0$ s and $\omega_5=85$ s; 4) $\omega_4=0$ s and $\omega_5=99$ s; 5) $\omega_5=115$ s. Thus, this robot waiting time determines an optimal feasible schedule for the close-down process. The Gantt chart in FIG. **4** shows the simulation result that takes 623 s to finish the close-down process.

Example 2

[0157] The flow pattern is (1, 1, 1, 1). $\alpha=5$ s, $\alpha_0=10$ s, $\mu=2$ s, $a_1=85$ s, $a_2=120$ s, $a_3=110$ s, $a_4=85$ s, and $\delta_i=20$ s, $1\leq i\leq 4$.

[0158] It follows from (3.5)-(3.8) that, one has $\vartheta_{1L}=116$ s, $\vartheta_{1U}=136$ s, $\vartheta_{2L}=146$ s, $\vartheta_{2U}=166$ s, $\vartheta_{3L}=136$ s, $\vartheta_{3U}=156$ s, $\vartheta_{4L}=111$ s, $\vartheta_{4U}=131$ s, and $\psi_1=75$ s. By Theorem 3.2, the single-arm cluster tool is schedulable. For the steady state, an optimal feasible schedule is obtained by setting $\omega_0=10$ s, $\omega_1=\omega_2=0$ s, $\omega_3=15$ s, and $\omega_4=46$ s. Then, the cycle time of the system under the steady state is 146 s. For this example, $[\vartheta_{1L}, \vartheta_{1U}] \cap [\vartheta_{2L}, \vartheta_{2U}] \cap \ldots \cap [\vartheta_{nL}, \vartheta_{nU}] = \emptyset$ holds since the differences between each step's workload are too large. By the proposed LPM, an optimal feasible schedule is found for the close-down process, during which the robot waiting time is set as follows: 1) From M_{c1} to M_{c1}, $\omega_1^1=\omega_2^1=0$, $\omega_3^1=15$, $\omega_4^1=46$ s; 2) From M_{c2} to M_{c3}, $\omega_2^2=0$ s, $\omega_3^2=35$ s and $\omega_4^2$55 s; 3) From M_{c3} to M_{c4}, $\omega_3^3=5$ s and $\omega_4^3=89$ s; 4) From M_{c4} to M_{ce}, $\omega_4^4=85$ s. The Gantt chart in FIG. **5** shows the simulation result that takes 468 s to finish the close-down process.

[0159] Semiconductor industry has shifted to larger size wafers and smaller lot production. Frequently, the wafer fabrication in the cluster tools switches from one size of wafer lot to another. This leads to many transient switching states, including start-up and close-down process. In some wafer fabrication process, quality products require that a processed wafer should leave the processing module within a given limit time to avoid its excessive exposure to the residual gas and high temperature inside a module. Such time constraints complicate the optimization issue for scheduling a close-down process. The problem and its solution are not seen in the existing research of scheduling cluster tools. This invention develops a Petri net model to analyze the time properties of this close-down process with time constraints. Based on it, the present invention proposes a closed-form algorithm and a linear programming model to regulate the robot waiting time for balanced and unbalanced workload situations, respectively, thereby finding an optimal schedule. The proposed methods are highly efficient.

[0160] The embodiments disclosed herein may be implemented using general purpose or specialized computing devices, computer processors, or electronic circuitries including but not limited to digital signal processors (DSP), application specific integrated circuits (ASIC), field programmable gate arrays (FPGA), and other programmable logic devices configured or programmed according to the teachings of the present disclosure. Computer instructions or software codes running in the general purpose or specialized computing devices, computer processors, or programmable logic devices can readily be prepared by practitioners skilled in the software or electronic art based on the teachings of the present disclosure.

[0161] In some embodiments, the present invention includes computer storage media having computer instructions or software codes stored therein which can be used to program computers or microprocessors to perform any of the processes of the present invention. The storage media can include, but is not limited to, floppy disks, optical discs, Blu-ray Disc, DVD, CD-ROMs, and magneto-optical disks, ROMs, RAMs, flash memory devices, or any type of media or devices suitable for storing instructions, codes, and/or data.

[0162] The present invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The present embodiment is therefore to be considered in all respects as illustrative and not restrictive. The scope of the invention is indicated by the appended claims rather than by the foregoing description, and all changes that come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

What is claimed is:

1. A computer-implemented method for scheduling a cluster tool for a close-down process, the cluster tool comprising a single-arm robot for wafer handling, loadlocks for wafer cassette loading and unloading, and n process modules each for performing a wafer-processing step with a wafer residency time constraint where the ith process module, $i \in \{1, 2, \ldots, n\}$, is used for performing Step i of the n wafer-processing steps for each wafer, the method comprising:

determining, by a processor, a lower workload ϑ_{iL} of Step i as follows:

$$\vartheta_{iL}=a_i+4\alpha+3\mu,\ i \in N_n\backslash[1];$$

$$\vartheta_{1L}=a_1+3\alpha+\alpha_0+3\mu;$$

determining, by a processor, an upper workload ϑ_{iU} of Step i as follows:

$$\vartheta_{iU}=a_i+4\alpha+3\mu+\delta_i,\ i \in N_n\backslash[1];$$

$$\vartheta_{1U}=a_1+3\alpha+\alpha_0+3\mu+\delta_1;$$

determining, by a processor, that the workloads are balanced among the Steps if $[\vartheta_{1L}, \vartheta_{1U}] \cap [\vartheta_{2L}, \vartheta_{2U}] \cap \ldots \cap [\vartheta_{nL}, \vartheta_{nU}] \neq \emptyset$;

determining, by a processor, a robot waiting time ω_i^d, $d\leq i\leq n$, $0\leq d\leq n-1$, and ω_n^n as follows:

let $\psi_{c0}=\psi_1$, during the period from M_{cd} to $M_{c(d+1)}$, $1\leq d\leq n-1$, let $\vartheta_{max}=\max\{\vartheta_{iL}, i\in N_n\backslash N_{d-1}\}$, $\omega_i^d=0$, $i\in N_n\backslash N_{d-1}$, and $\omega_n^d=\max\{\vartheta_{dmax}-\psi_{c(d-1)}, 0\}$, where $\psi_{c(d-1)}=2(n-d+2)\mu+2(n-d+2)\alpha$, $2\leq d\leq n$;

during the period from M_{cn} to M_{ce}, let $\omega_n^n=a_n$;

determining, by a processor, a schedule for the close-down process based on the robot waiting time determined;

a_i, $i \in N_n$, is a time that a wafer is processed in the ith process module;

δ_i is the wafer residency time constraint of Step i, given by a pre-determined longest time for which a wafer in the ith process module is allowed to stay therein after this wafer is processed;